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Optimizing the Temperature of Hot outlet Air of Vortex Tube using Taguchi Method.

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Abstract

Vortex tube produces hot and cold streams from inlet pressurized gas. Though mainly used for spot cooling purposes, it may also be used for heating / pre-heating applications. In this work, the effect of - inlet air pressure, hot tube length, hot tube internal diameter, orifice diameter, and nozzle diameter, on hot-outlet air temperature is analyzed. Taguchi's parameter design approach is used to optimize the response. Above parameters are considered at three levels each. L-27 Orthogonal Array is used for experimentation with two replicates. From the ANOVA table, all the parameters considered are found to be statistically significant. Relevant graphs are drawn; optimum response value at optimal factor levels is predicted. Through confirmatory test, experimental results are validated.

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Key words: Vortex Tube; Hot Temperature; Orthogonal Array; Parameter Design; ANOVA.

Nomenclature:
D_t - Internal diameter of the hot tube, in mm
L - Length of the hot tube, in mm
P – Inlet air Pressure, Kgf / cm^2
D_o - Diameter of the Orifice, in mm
D_n - Diameter of the Nozzle, in mm
The response variable is **T_h** - Temperature of hot outlet air (in degree centigrade)
T_h –i: Temperature of hot outlet air; ith replicate (in degree centigrade)

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1.0 Introduction

A vortex tube uses compressed air or any gas as input, and separates the input gas into hot and cold streams. The volume and temperature of these two air streams are adjustable using a conical valve built into the hot air exhaust. Compressed air is supplied to the vortex tube and passes through the nozzle, located in the vortex chamber, tangential to an internal counter bore. Thus vortex motion is given by nozzle to the air. This spinning stream of air passes down the hot tube. In a counter flow type of vortex tube, conical valve at the other (hot) end of the tube allows some of the warmed air to leave the vortex tube. Remaining air heads back, down the tube as a smaller inside vortex in the low-pressure area within the outer vortex. This inner vortex loses heat and exhausts as cold air through the orifice, kept in the cold tube after the vortex chamber. The outer vortex is under higher pressure than the inner vortex (because of centrifugal force) and therefore the temperature of the outer vortex air is higher than that of the inner vortex air. In a parallel flow type of vortex tube, the cold air exhaust is through the conical valve. Several studies revealed that performance of counter flow type of vortex tube is superior to that of parallel flow type of vortex tube. The main parts of the vortex tube are:

1. Hot and Cold tubes 2. Vortex chamber 3. Orifice/ Diaphragm
4. Nozzle and 5. Conical valve

1.1 Literature Review:

Several studies focused their attention on optimizing the performance of the vortex tube with respect to its construction design features, input parameters and so on. Other studies tried to analyze the heat transfer phenomenon within the vortex tube using Computational Fluid Dynamics (CFD) and other numerical/mathematical procedures. It is mainly the spot cooling ability of the vortex tube that motivated studies on the vortex tube and hence optimization of cold outlet temperature of the vortex tube has been the major concentration of these studies. Few studies attempted to optimize the temperature difference between the hot and cold outlet temperatures for different input parameters. A.M. Pinar et. al. [1] conducted studies to maximize the temperature difference between the hot and cold outlet temperatures using Taguchi method. The study revealed that all the three parameters considered and their two way interactions have significant effect on the response, statistically. J. Prabakaran et. al. [2] studied the effect of orifice diameter and pressure and concluded that they have significant effect on the performance of the vortex tube. The effects of nozzle aspect ratio and nozzle number on the performance of a vortex tube are studied by Mete Avci [3]. Two sets of vortex generator (a single nozzle set with aspect ratio of AR = 0.25, 0.44 and 0.69 and a multiple nozzle set with 2 and 3 nozzle number having the same total flow area) are used for experimentation under different inlet pressures. The experimental results reveal that the increase in the nozzle aspect ratio leads to the decrease in the temperature difference between the cold and hot streams. The results also showed that single nozzle yields better performance than 2 and 3 nozzles. Again, A.M. Pinar et. al. [4] in their other work, considered inlet pressure, nozzle number and cold mass fraction as affecting factors, each at three levels. It was observed that the quality characteristic-temperature difference increased with the increase of inlet pressure and cold mass fraction and decreased with the increase in nozzle number. L27 OA was used for experimentation and Taguchi method was used for parameter optimization. Y. Xue et.al. [5] focused their study on the effect of vortex angle on the efficiency and performance of the vortex tube. Vortex angle generator was used to form different vortex angles. It was shown that the vortex angle played an important role in both the separation of cold and hot flows and vortex tube performance. A smaller vortex angle demonstrated a larger temperature difference and better performance for the heating efficiency of the vortex tube. The effect of cooling the vortex tube on the temperature separation (Ti – Tc) was studied by S. Eiamsa-ard et. al. [6]. It was found that cooling efficiency in the vortex tube was higher when the tube was externally cooled than when it was not cooled, operating under similar conditions. Several experimental trials have been carried out by O. Aydin et.al. [7], to investigate the effect of some new design features (use of helical swirl flow generator) at different pressures and the effect of helical swirl length for various values of L/D and the inlet pressures on the temperature separation. It is concluded that the effect of helical swirl length on the temperature separation changes critically according to the value of L/D. Effects of position, diameter and angle of a mobile plug located at the hot outlet side, and of supply pressures and number of nozzles on the temperature difference between hot and cold outlet streams is experimented by K. Dincer et.al. [8]. Better results are obtained for -the plug diameter of 5 mm, tip angles of 30^0 and 60^0, 4 nozzles and by keeping plug location at the far extreme end. Using Response Surface methodology, parameter optimization of inlet pressure, diameters of nozzles and orifices with the response variable being cold temperature of vortex tube is attempted by J. Prabakaran et.al. [9]. It is found that inlet pressure and diameter of nozzle are significant factors that affect the temperature of cold stream of air (response). Insights into Taguchi method, parameter design, preparation and interpretation of ANOVA are explained by Philip J. Ross [10]. A numerical study has been carried out by P. Nader et.al. [11] by using a 3D compressible turbulent CFD model to investigate the effect of L/D ratio on the cold temperature difference and efficiency. Among the L/D ratios used, an L/D ratio of 9.3 yields better performance of the vortex tube. Vortex tube is modified with a new nozzle with equal gradient of Mach number, new intake flow passage of nozzles with equal flow velocities, and a new kind of a diffuser that reduces friction loss of air flow energy at the hot end by Y.T. Wu et. al. [12]. The experimental results indicated that these modifications remarkably improve the performance of vortex tube. Effect of conical shape of cold tube is investigated by M. Guen et.al. [13] by making the cold tube diverging towards the cold exit. Results of the CFD analysis supported by experimental results suggest that 20^0 vortex angle yields the best results. Mohammad O. Hamdan et.al. [14] carried out experiments to study the effect of nozzle parameters viz., number of nozzles, nozzle inlet angle, nozzles arrangement and inlet pressure, cold mass fraction and vortex stopper location, on the energy separation of the vortex tube. Conclusion is inlet pressure is impetus for and cold mass fraction, number of nozzles, and nozzle inlet angle have strong impact on energy separation in the vortex tube. As vortex stopper moves far from vortex generator, the COP increases. Finally, symmetry or asymmetry of nozzles has insignificant effect on the performance of vortex tube.

Though the vortex tube is popular for cooling applications, temperature of the hot air coming out from the hot tube is considered as the response variable in the present experimentation, suggesting that the vortex tube can also be used for heating applications or for any preheating purpose. Thus this work is a novel one, as temperature of the hot air is considered as response variable instead of cold temperature or temperature difference.

The Design of Experiments with optimization of control parameters to obtain best results is achieved by the Taguchi Method. "Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and Taguchi's

Signal-to-Noise ratios (S/N ratios), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results.

Orthogonal Arrays (OAs) represent a versatile class of combinatorial arrangements useful for conducting experiments to determine the optimum mix of a number of factors in a product to maximize the yield. The OAs should possess Orthogonality and balance properties. Taguchi's orthogonal arrays are highly fractional orthogonal designs. These designs can be used to estimate main effects using only a few experimental runs. These designs are not only applicable to two level factorial experiments, but also can investigate main effects when factors have more than two levels. Designs are also available to investigate main effects for certain mixed-level experiments where the factors included do not have the same number of levels. These designs require the experimenter to assume that certain interaction effects are unimportant and can be ignored. Depending on the no. of factors and the level of each factor considered, the appropriate OA can be selected. In the present work, L-27 orthogonal array is chosen, to carry out experiments.

1.2 Objective:

The objective of this work is to study, using Taguchi method, the influence of the controllable parameters selected, viz., inlet air Pressure, Length of the vortex (hot) tube, Diameter of the vortex(hot) tube, Diameter of the orifice / diaphragm, and Diameter of the nozzle, on the Temperature of hot outlet air of the vortex tube.

2.0 Experimental work:

By applying Taguchi method, the performance of vortex tube can be optimized easily. The number of iterations / the experimental trials can be reduced. For a problem involving five factors each at three levels, the total number of trials needed (full factorial) is $3^5 = 243$, whereas only 27 trials are run in the present work to study the effect of those parameters on the output response selected.

The vortex tube used in the present work is of counter flow type using one nozzle. Following the steps given in Fig. 1, the control factors are identified that are expected to affect the response. L-27 OA is selected as appropriate for the requirements and the array is adapted to accommodate the present five control factors, each at 3 levels. Experimentation is carried out and response values are noted for all the 27 run conditions. Two replicates have been carried out. Analysis is done and resultant graphs and ANOVA table are obtained. Factor effects are studied, optimum levels for the factors are determined. A confirmatory test is run to validate the experimental results with the optimal settings for the factors.

The factors considered with their three levels are as follows:

D_t- Internal diameter of the hot tube (11 mm, 14 mm, 17 mm)
L- Length of the hot tube (120 mm, 150 mm, and 180 mm)
P- Pressure, Kgf / cm^2 (1, 2, 3); **D_o**- Diameter of the Orifice (6 mm, 8 mm, 10 mm)
D_n- Diameter of the Nozzle (11 mm, 14 mm, 17 mm)
The response variable is T_h - Temperature of hot outlet air, (in degree centigrade)

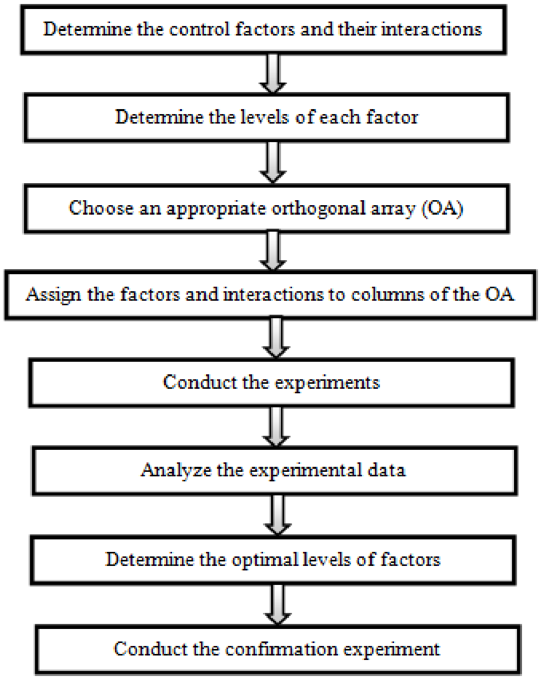

Fig. 1: Flow chart depicting Taguchi methodology

2.1 The L-27 OA modified for the parameter level combinations:

The standard L-27 array layout in coded form is taken and the three level values of the five factors selected are appropriately substituted to get Table-1. Two columns are added to the right side for noting the replicates T_h-1 and T_h-2 of response values. The factors are assigned to columns considering ease of experimentation not violating the properties of the table.

Table 1: The L-27 OA modified for input parameter level combinations

L (mm)	D_t (mm)	D_n (mm)	D_o (mm)	P (Kgf/cm^2)	T_h-1 (^{0}C)	T_h-2 (^{0}C)
120	11	11	6	1	35	35
120	11	11	6	2	38	39
120	11	11	6	3	41	41
120	14	14	8	1	38	41
120	14	14	8	2	41	44
120	14	14	8	3	44	48
120	17	17	10	1	38	41
120	17	17	10	2	41	43
120	17	17	10	3	45	45
150	11	14	10	1	34	35

150	11	14	10	2	37	37
150	11	14	10	3	38	41
150	14	17	6	1	38	40
150	14	17	6	2	43	45
150	14	17	6	3	46	47
150	17	11	8	1	34	35
150	17	11	8	2	36	36
150	17	11	8	3	40	41
180	11	17	8	1	45	42
180	11	17	8	2	48	46
180	11	17	8	3	50	49
180	14	11	10	1	36	40
180	14	11	10	2	37	41
180	14	11	10	3	41	46
180	17	14	6	1	36	39
180	17	14	6	2	41	42
180	17	14	6	3	45	46

3.0 Results Analysis and Discussion:

The results obtained after experimentation are analyzed using Minitab software. The Response table for means, and ANOVA table are derived to study the significance of parameters on the response. Graphs are drawn to depict the effects of parameters and their levels on the response variable.

3.1 Interpretation of the graphs and Tables:

The Main effects plot for the Means (Fig. 2) indicates the following:

- Higher the Pressure and Nozzle diameter, higher is the hot outlet temperature
- Peak points in the graph show that the optimum response (Higher Hot temperature) is achievable with the optimal factor settings at P = 3Kgf / cm^2, D_t = 14 mm, D_n =17 mm, D_o = 8 mm, L = 180 mm

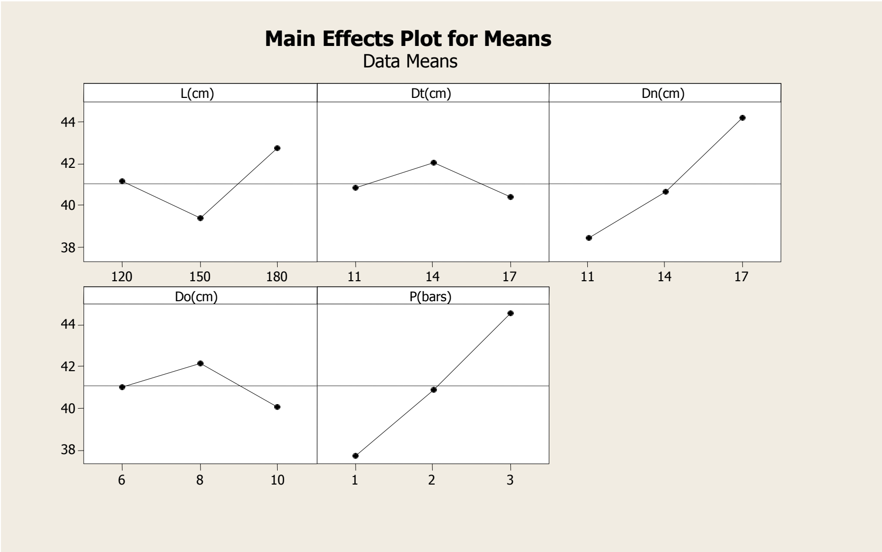

Fig. 2 Main Effects Plot for Means (Response Vs. Factor levels)

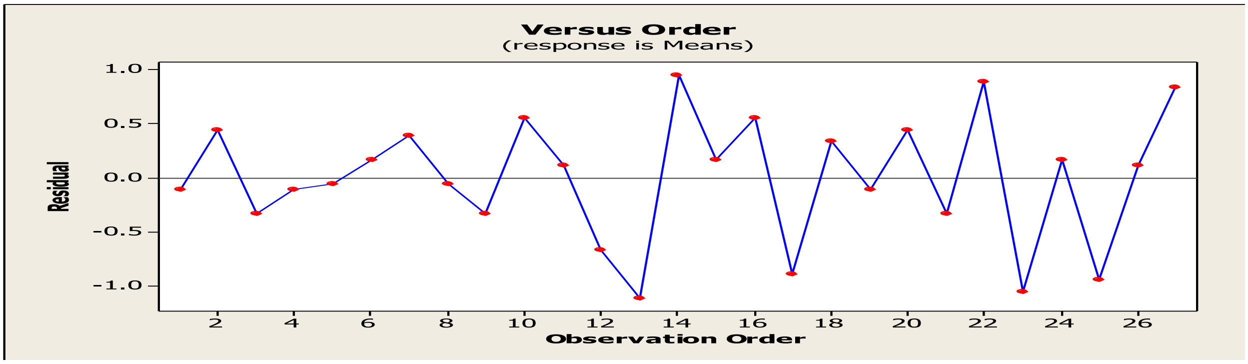

Fig. 3: Residual vs. Order graph

From Fig. 3, as all the points are randomly scattered about the centre line (0-line), the observation / run order does not have effect on the experimental results.

Table 2: Analysis of Variance (ANOVA) for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
L(mm)	2	62.389	62.389	31.1944	57.96	0.000
Dt(mm)	2	15.722	15.722	7.8611	14.61	0.000
Dn(mm)	2	143.056	143.056	71.5278	132.9	0.000
Do(mm)	2	24.500	24.500	12.2500	22.76	0.000
P(bars)	2	174.389	174.389	87.1944	162.01	0.000
Residual Error	16	8.611	8.611	0.5382		
Total	26	428.667				

Table 3: Response Table for Means

Level	L(mm)	D_t (mm)	D_n (mm)	D_o (mm)	P (Kgf/cm^2)
1	41.00	40.61	38.44	40.94	37.89
2	39.06	42.00	40.39	42.11	40.83
3	42.78	40.22	44.00	39.78	44.11
Delta	3.72	1.78	5.56	2.33	6.22
Rank	3	5	2	4	1

The ANOVA table (Table 2) indicates that all the factors considered are statistically significant and Response table for Means (Table 3) gives the ranks of factors vis-à-vis their influence on the response.

3.2 Prediction of optimum mean response and factor levels by Taguchi method:

Optimum mean response value predicted by Taguchi method with standard deviation is:

S/N Ratio	Mean	St. Dev	Ln (St. Dev)
34.3166	**51.1329**	**2.43133**	0.829556

Factor levels used for prediction (Optimal Settings as given by Fig. 3)

L (mm)	D_t (mm)	D_n (mm)	D_o (mm)	P (Kgf/cm^2)
180	14	17	8	3

Predicted value of output response at the optimum settings is 51.1329 ºC with a standard deviation of 2.4313 ºC.

4.0 Confirmatory Test:

The confirmatory test is run with the above optimal settings for factors and the results are tabulated in Table- 4; the mean output response is calculated to be 50.2 ºC, with a standard deviation of 1.30384 ºC. These are matching the predicted values. Also % Error is calculated (with respect to predicted mean value of the response) to be 1.82 which is very low and acceptable. Thus the results are validated.

Table 4: Confirmatory Test (run at the optimal settings) Results

Trial No.	1	2	3	4	5	Mean	St. Dev.
Hot outlet temperature, T_h (ºc)	49	50	49	52	51	50.2	1.30384

% Error (w.r.t. predicted mean) = ((51.1329 – 50.2) / 51.1329) x100 = 1.82

5.0 Conclusions:

It is concluded that all the parameters considered are found to have significant effect on the response statistically. For optimum hot outlet temperature, the settings of the parameters are: **L -** 180 mm; $\mathbf{D_t}$ **–** 14 mm **;** $\mathbf{D_n}$ – 17 mm; $\mathbf{D_o}$ – 8 mm; and **P –** 3 Kgf/cm^2. The results of this work are useful to motivate the industry to use the vortex tube for suitable heating applications too. This work may be useful to enhance the applications domain of the vortex tube, as temperature of the hot air is considered as response variable and optimized in the present work.

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